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Solar cooker with latent heat storage systems: A review

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ABSTRACT

Cooking with the sun has become a potentially viable substitute for fuel-wood in food preparation in much of the developing world. Energy requirements for cooking account for 36% of total primary energy consumption in India. The rural and urban population, depend mainly, on non-commercial fuels to meet their energy needs. Solar cooking is one possible solution but its acceptance has been limited partially due to some barriers. Solar cooker cannot cook the food in late evening. That drawback can be solved by the storage unit associated with in a solar cooker. So that food can be cook at late evening. Therefore, in this paper, an attempt has been taken to summarize the investigation of the solar cooking system incorporating with phase change materials (PCMs).

Contents

1. Introduction

India is blessed with good sunshine. Most parts of the country receive mean daily solar radiation in the range of 5–7 kWh/m^2, and have more than 275 sunny days in a year [1]. Solar cooking has been part of India's National Program since 1982. Parabolic and box-type solar cooker are low cost options for meeting the cooking energy needs as well as environmental protection. Even though over 600,000 box-type solar cookers have been sold so far in India and the large potential of solar cookers is yet untapped [2]. Hence, solar cooking has a high potential of diffusion in the country, and offers a viable option in the domestic sector. It is identified as an appropriate technology for Indian masses, and has numerous advantages such as no recurring costs, potential to reduce drudgery, high nutritional value of food, high durability, etc. In spite of these advantages, the main hurdles in its dissemination are reluctance to acceptance as it is a novel technology, intermittent nature of sunshine, limited space availability in urban areas, higher initial costs and convenience issues. The growing urban lifestyle also warrants faster cooking which is not possible in box solar cookers [3,4].

Solar energy is free, environmentally clean, and therefore is recognized as one of the most promising alternative energy recourses options. In near future, the large-scale introduction of solar energy systems, directly converting solar radiation into heat, can be looked forward to. However, solar energy is intermittent by its nature; there is no sun at night. Its total available value is seasonal and is dependent on the meteorological conditions of the location. Unreliability is the biggest retarding factor for extensive solar energy utilization. Of course, reliability of solar energy can be increased by storing its portion when it is in excess of the load and using the stored energy whenever needed. Energy storage is, therefore, essential to any system that depends largely on solar energy. It adjusts temporal mismatches between the load and the

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intermittent or variable energy source, thereby improving the system operability and utility. Solar radiation cannot be stored as such, so first of all an energy conversion has to be brought about and, depending on this conversion, a storage device is needed. Solar energy can be stored by thermal, electrical, chemical, and mechanical methods.

Energy consumption for cooking in developing countries is a major component of the total energy consumption, including commercial and non-commercial energy sources. Energy requirements for cooking account for 36% of total primary energy consumption in India. Most of the energy requirement for cooking is met by non-commercial fuels, such as firewood, agricultural waste and cow dung in rural areas and kerosene and liquid petroleum gas (LPG) in urban areas [5]. Utilization of solar energy for thermal applications, like cooking, heating and drying, is well recognized in tropical and semitropical regions. The different types of solar cookers developed for cooking are (i) concentrator type (ii) box-type and (iii) indirect type. Box-type solar cookers are more popular due to their simplicity of handling and operation. Solar cookers are used to cook the rice, vegetables, meat, bake cakes, etc. In India and many other countries, among the various types of solar cookers, the box-type solar cookers are becoming very popular. The detailed design, testing, theory and utility of the box-type solar cookers are well developed [6–9]. But, the use of these solar cookers is limited because they do not have any storage, i.e. these cookers cannot be used in partial cloudy days and/or days or in late evening hours. If the storage of solar energy can be provided in a solar cooker, then there is a possibility of cooking food during partial clouds and/or in late evening hours and hence, the storage will increase the utility and reliability of the solar cookers.

PCM take advantage of latent heat that can be stored or released from a material over a narrow temperature range. PCM possesses the ability to change their state with a certain temperature range. These materials absorb energy during the heating process as phase change takes place and release energy to the environment in the phase change range during a reverse cooling process. Basically, there are three methods of storing thermal energy: sensible, latent and thermo-chemical heat or cold storage. Thermal energy storage in solid-to-liquid phase change employing phase change materials (PCMs) has attracted much interest in solar systems due to the follow advantages:

(i) It involves PCMs that have high latent heat storage capacity.
(ii) The PCMs melt and solidify at a nearly constant temperature.
(iii) A small volume is required for a latent heat storage system, thereby the heat losses from the system maintains in a reasonable level during the charging and discharging of heat.

A large number of solid–liquid PCMs have been investigated for heating and cooling applications [10–18]. The PCM to be used in the design of any thermal storage systems should pass desirable thermophysical, kinetics and chemical properties which are given in Table 1 [10,18]. The ideal phase change material to be used for latent heat storage system must meet following requirements: high sensitive heat capacity and heat of fusion; stable composition; high density and heat conductivity; chemical inert; non-toxic and non-inflammable; reasonable and inexpensive. In the nature, the salt hydrates, paraffin and paraffin waxes, fatty acids and some other compounds have high latent heat of fusion in the temperature range from 0 to 150 °C that is interesting for solar applications.

Recently, the incorporation of PCM in different applications has grown interest to the researcher. PCM review article are available for any one application except solar cookers. Therefore, in this paper, an attempt has been taken to summarize the investigation of the solar cooking system incorporating with PCMs. This paper is a compilation of much of practical information on few selected PCMs used in a box-type solar cooker and concentrator solar cooker. This review will help to find the design, development of suitable PCM storage unit for solar cookers.

2. Solar cookers with latent heat storage materials: a review

Ramadan et al. [19] designed a simple flat-plate solar cooker with focusing plane mirrors and energy storage capabilities constructed by the locally available materials in Tanta University. The temperature distributions during the test periods through the absorbing plate, the glass covers, the cooking pot, the cooking fluid, the storage medium and the ambient were determined. The diurnal variations of incident global solar insolation were presented. The utilization of sensible heat storage medium such as sand was investigated thoroughly. A jacket of sand (1/2 cm thick) around the cooking pot has improved the cooker performance tremendously. The temperature differences between the heat source and the heat sink during the test time were determined and the results were discussed. Six hour per day of cooking time has been recorded. Approximately 3 h/day of indoor cooking has been achieved. Overall energy conversion efficiency up to 28.4% has been obtained which was considered the best among other solar cookers in the literature. The possibility of using a phase change material as a storage medium to obtain longer cooking periods was studied. A thin layer of the salt hydrate $Ba(OH)_2 \cdot 8H_2O$ as a jacket around the cooking pot was suggested.

Bushnell [20] designed, developed and evaluates a solar energy storing heat exchanger as a step toward a solar cooking concept. The solid–solid transition of pentaerythritol is the principal mechanism for energy storage. The methods for describing the system performance were explained and applied to a test system containing a controllable replacement for the solar input power. This first stage of this research work followed by a heat exchanger, which was connected to a concentrating array of CPC cylindrical troughs. Author also described the size of the solar collector area and mass of PCM mass needed in order to provide adequate energy for several family-size meals with sufficient storage to cook at night and 1 or 2 days later. Bushnell and Sohi [21] also designed a modular phase change heat exchanger with pentaerythritol used as a PCM for thermal storage (solid–solid phase change at 182 °C) was tested in an oven by circulating heat transfer oil which was heated electrically in a manner to simulate a concentrating solar collector. Thermal energy retention times and cooking extraction times were determined, and along with the efficiencies, were

Table 1
Main desirable properties of phase change materials.

Thermal properties	Physical properties	Kinetic properties	Chemical properties	Economics
Suitable phase-transition temperature	Favorable phase equilibrium	No supercooling	Long-term chemical stability	Abundant
High latent heat of transition	High density	Sufficient crystallization rate	Compatibility with materials of construction	Available
Good heat transfer	Small volume change		No toxicity	Cost effective
	Low vapor pressure		No fire hazard	

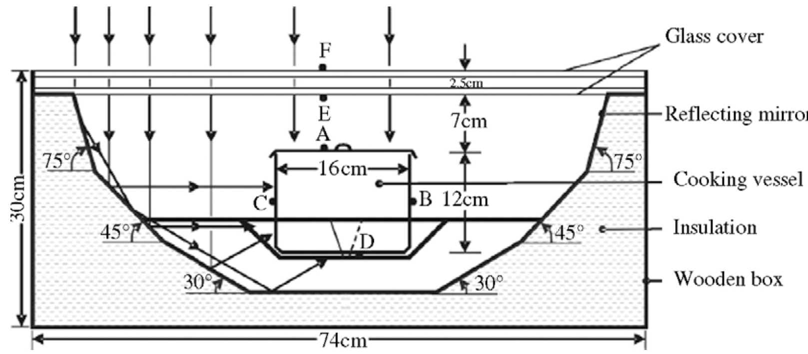

Fig. 1. Schematic diagram of the solar cooker by Domanski et al.

compared with the results previously reported for a non-modular heat exchanger.

Domanski et al. [22] investigated the possibility of cooking during non-sunshine hours using PCM. They designed the storage-cooking vessel for non-sunshine hours (Figure 1). Two concentric cylindrical vessels (0.0015-m thick), made from aluminum, are connected together at their tops using four screws to form a double-wall vessel with a gap between the outer and inner walls. The outer vessel has a diameter of 0.18 m and its height equals 0.12 m. The inner vessel has dimensions of 0.14 and 0.1 m for diameter and height respectively. The annular gap between the outer and inner vessels is 0.02 m. This gap is covered with a removable aluminum cover into which three circular holes were drilled to allow inserting of thermocouples and permit direct visualization during filling or removing of the PCMs. A circular aluminum cover is used as the lid for the inner vessel. The outside surfaces of the outer vessel and the covers are painted using ordinary black paint for maximum absorption of available solar radiation. The gap between the outer and inner vessels is filled with 1.1 kg of stearic acid, 95% pure, or 2 kg of magnesium nitrate hexahydrate, 99% pure, which leaves sufficient space for expansion of the PCMs on melting. They reported that performance depends on the solar irradiance, mass of the cooking medium, and the thermo physical properties of the PCM. The overall efficiency of the cooker during discharging was found to be three to four times greater than that for steam and heat-pipe solar cookers, which can be used for indoor cooking. In such a type of design, the rate of heat transfer from the PCM to the cooking pot is slow, and more time is required for cooking the evening meal.

Buddhi and Sahoo [23] designed a box-type solar cooker with latent heat storage for the composite climatic conditions of India. The experimental results demonstrate the feasibility of using a phase change material as the storage medium in solar cookers. It also provides a nearly constant plate temperature in the late evening. The experimental results have also been compared with those of a conventional solar cooker. Commercial-grade stearic acid (melting point is 55.1 °C and latent heat of fusion is 160 kJ/kg) was used as a PCM. Figure 2 shows the sketch of a box-type solar cooker for one vessel having a PCM to store the solar energy. The cooker consists of an aluminum absorbing tray ‘A’ of dimensions 0.28 m × 0.28 m at the bottom, 0.40 m × 0.40 m at the top for the double glass lid, and the vertical depth of the tray is 0.08 m. The thickness of the aluminum sheet was 0.006 m. In the centre of the absorbing plate, a cylindrical container of 0.165 m diameter and 0.02 m in depth has been welded (shown in Figure 2 by ‘C’), and the cooking pot is to be kept tightly in it. This container will provide a better heat transfer from the absorbing plate and PCM. Moreover, aluminum fins were also provided at the inner side of the tray and cylindrical container. The outer tray ‘B’ of size 0.40 m × 0.40 m × 0.108 m is also made from the same aluminum sheet. The distance between tray ‘A’ and tray ‘B’ was kept at 0.025 m on the bottom side. Tray ‘B’ was filled with 3.5 kg of commercial-grade stearic acid and it was made sure that the PCM should be in good contact with the bottom side of tray ‘A’. These two trays were encased in an aluminum box of dimensions 0.5 m × 0.5 m × 0.14 m. The space between tray ‘B’ and the casing was filled with glass-wool to provide thermal insulation to the bottom and sides of the solar cooker. The absorbing tray was provided with a double glass lid (0.4 m × 0.4 m) hinged to one side of the casing at the top. The aluminum cooking pot (0.16 m in diameter and 0.06 m in height) with cover was kept in the pot container ‘C’. The aluminum tray ‘A’, cooking pot and its cover were painted with a dull black paint on the outside.

Experiments with solar cookers indicate that foods are cooked at temperatures between 95 and 97 °C. No appropriate and promising PCM, having a melting temperature between 95 and 105 °C is available in the literature. Therefore, Sharma et al. [24] used commercial-grade acetamide (melting point is 82 °C and latent heat of fusion is 263 kJ/kg) as a latent heat storage material, which has the nearest melting temperature out of the quoted materials in the literature. They designed, fabricated and tested a cylindrical PCM storage unit for a box-type solar cooker to cook the food in the late evening. This unit surrounds the cooking vessel, the rate of heat transfer between the PCM and the food is higher, and cooking can be faster. For this purpose, a PCM container to hold the cooking vessel was designed and fabricated as shown in Fig. 3. It has two hollow concentric aluminum cylinders of diameters 18 and 25 cm, and is 8 cm deep with a 2 mm thickness. The space between the cylinders was filled with acetamide as a PCM. The dimensions of the vessel used for cooking were 17.5 and 10 cm in diameter and height, respectively, and it can be inserted inside the PCM container for cooking purposes. To enhance the rate of heat transfer between the PCM and the inner wall of the PCM container, eight fins (1 cm × 3 cm) were welded at the inner wall of the PCM container. They reported that by using 2.0 kg of acetamide as a latent heat storage material, the second batch of food could be cooked if it is loaded before 3:30 p.m. during the winter season. Cooking of three batches a day during summer and two batches a day during winter were made successfully with the designed storage unit. From the experimental results, authors conclude that (i) the storage of solar energy does not affect the performance of the solar cooker for noon cooking and (ii) if a PCM having a melting temperature between 105 and 110 °C is used, the cooking with the present design will be possible even during the night.

As Sharma et al. [24] recommended that the melting temperature of a PCM should be between 105 and 110 °C for evening cooking. Therefore, there was a need to identify a storage material with appropriate melting point and quantity, which can

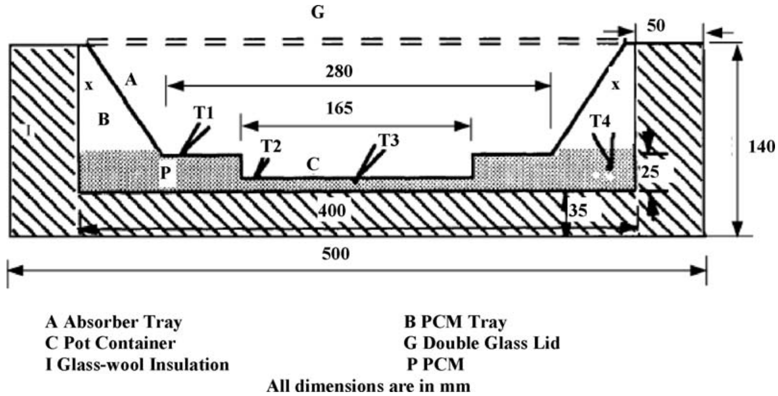

Fig. 2. Schematic diagram of the box of a solar cooker with storage.

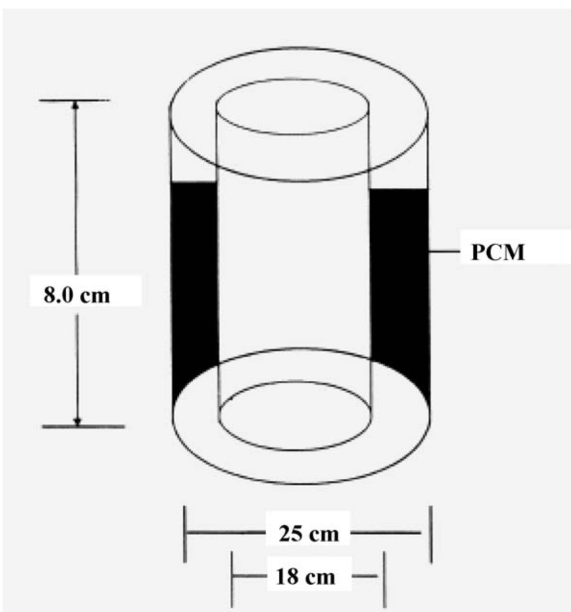

Fig. 3. Schematic diagram of latent heat storage unit.

cook the food in the late evening. Later, Buddhi et al. [25] used acetanilide (melting point is 118.9 °C and latent heat of fusion is 222 kJ/kg) as a PCM for night cooking. To conduct the cooking experiments with the PCM storage unit, a double glazed (glass covers) box-type solar cooker having a 50 cm × 50 cm aperture area and being 19-cm deep was used. The unit has two hollow concentric aluminum cylinders of diameter 20 and 30 cm and 12.5-cm deep of 2-mm thickness. The space between the cylinders was first filled with 2.25 kg acetanilide used as the PCM to conduct the cooking experiments with a single existing reflector. The dimensions of the vessel used for cooking were 19 and 15 cm in diameter and height, respectively, and it can be inserted inside the PCM storage unit for cooking purposes. To enhance the rate of heat transfer between the PCM and the inner wall of the PCM container, 8 fins (1 cm × 3 cm) were welded at the inner wall of the PCM container. Food was not cooked if it was loaded at 18.00 h. So that, to cook the food in the late evening, an additional 1.75 kg of PCM was filled in the PCM storage unit. As it was not possible to melt this quantity (4.0 kg) of PCM with the single reflector and to store a larger quantity of heat in a PCM, more input solar radiation would be required. Hence, authors added two more reflectors to enhance the incident solar radiation on the glass cover. In this solar cooker, three reflectors were provided, i.e., the middle reflector was mounted with a hinge and had rotation only about the horizontal axis. The other two reflectors were fixed by a ball and socket mechanism in the left and right sides of the reflector (Figure 4). This pair of reflectors has three degrees of freedom, i.e., they can have movement about the horizontal axis, and vertical axis and can

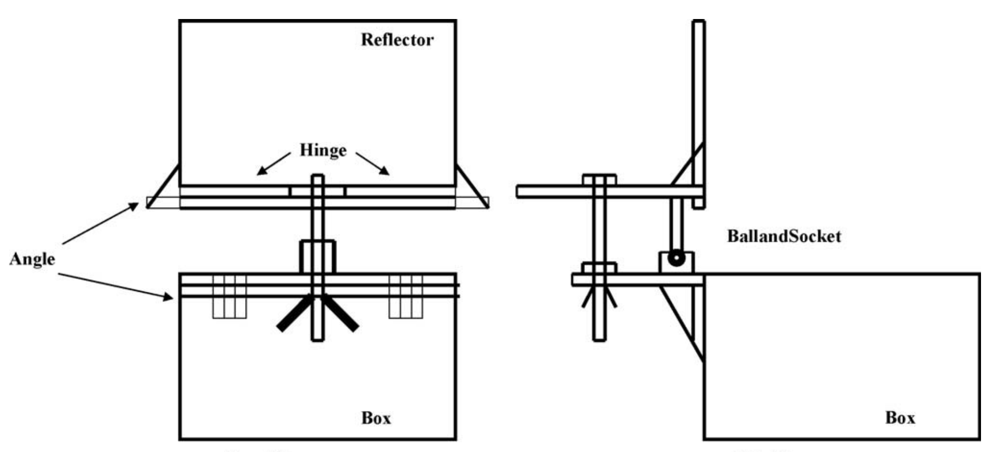

Fig. 4. A schematic sketch of the ball and socket mechanism of right and left side reflectors.

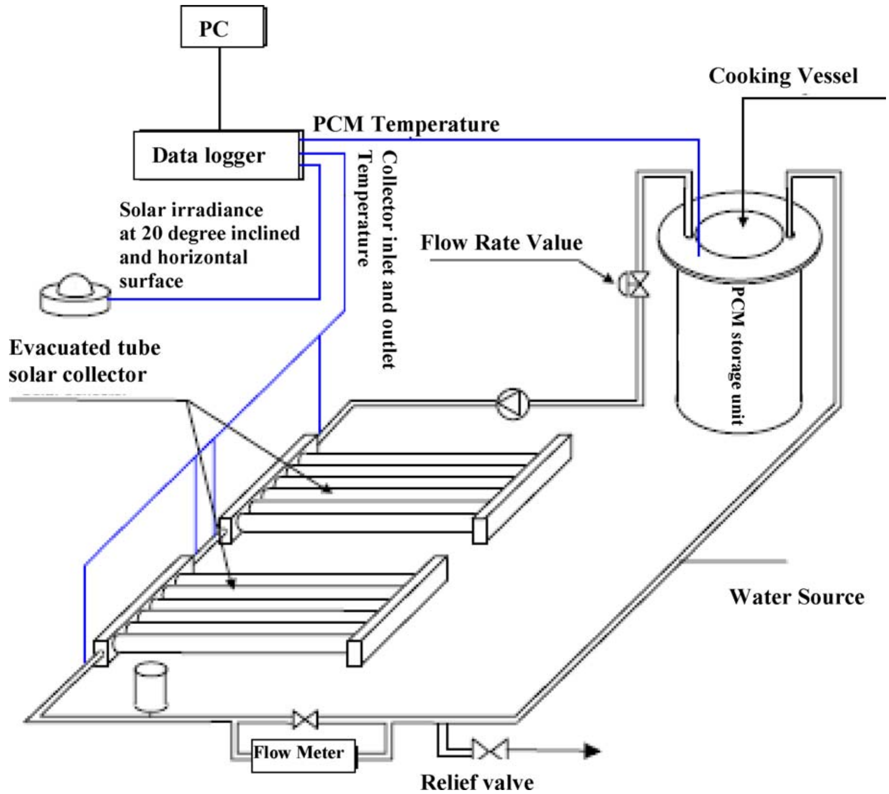

Fig. 5. Outline of the prototype solar cooker based on evacuated tube solar collector with PCM storage unit.

rotate about both the axes. By these mechanisms, efforts were made to keep the reflected solar irradiance on the absorber surface to enhance the incident solar radiation on the glass cover during the course of the sun exposure experiments. From the experimental results, authors conclude that the cooking experiments were successfully conducted for the evening time cooking up to at 20.00 h with 4.0 kg of PCM used in the storage unit.

Sharma and Sagara [26] and Sharma et al. [27,28] developed a solar cooker based on evacuated tube solar collector (ETSC) with PCM storage, as shown in Figure 5. It consists of an ETSC, a closed loop pumping line-containing water as heat transfer fluid (HTF), a PCM storage unit, cooking unit, pump, relief valve, flow meter, and a stainless steel tubing heat exchanger. The PCM storage unit has two hollow concentric aluminum cylinders, and its inner and outer diameters were 304 and 441 mm, respectively, and were 420-mm deep and 9-mm thick. The space between the cylinders was filled with 45 kg commercial-grade erythritol (melting point is 118 °C and latent heat of fusion is 339.8 kJ/kg) used as the PCM. A pump (370 W) circulates the heated water (HTF) from the ETSC through the insulated pipes to the PCM storage unit using a stainless steel tubing (diameter 21.6 mm) heat exchanger that wraps around the cooking unit in a closed loop as shown in Fig. 5. During sunshine hours, heated water transfers its heat to the PCM and is stored in the form of latent heat through a stainless steel tubing heat exchanger. This stored heat is utilized to cook the food in the evening time or when sun intensity is not sufficient to cook the food. They concluded that system was able to cook successfully twice (noon and evening) in a single day during Japanese summer months. Noon cooking did not affect evening cooking, and the evening cooking using the heat through PCM storage unit was found to be faster than noon cooking. The PCM did not melt in January (winter season) in Japanese climate. Cooking experiments also showed that the PCM storage unit was able to store an adequate amount of heat for noon and evening cooking and was also capable to keep PCM temperatures (near 75 °C) until the next morning. Experiments and analysis indicated that the prototype solar cooker yielded satisfactory performance in spite of low heat transfer; the modified design of heat exchanger in the thermal storage unit will enhance the rate of heat transfer in the present set-up. The cooker performance under a variety of operating and climatic conditions was studied at Mie, Japan.

Some PCMs are white, like water, in physical appearance in the liquid state and can transmit solar radiation, but no efforts have been made to study the transmittance of these materials. Latent heat thermal energy storage materials usually have low thermal conductivity, and these materials can act as self-insulators. Because of the poor thermal conductivity and good transmittance, these materials can be used as transparent insulation and can also trap the heat. Buddhi and Sharma [29] were conducted a study to measure the transmittance of solar radiation through a PCM in the liquid and semi-liquid phases. Commercial-grade stearic acid (white like water in the liquid phase) was used as a PCM (melting point is 64.6 °C and latent heat of fusion is 155 kJ/kg) to study its transmitivity. In this study, the transmittance of commercial-grade stearic acid for different thicknesses and temperatures were measured. That study indicated that the effect of temperature on the transmittance of stearic acid in the liquid phase is not significant. However, it is highly dependent on temperature during the solidification process. Because of its low thermal conductivity and high transmitivity, it can be used as a transparent insulating material.

In 2003, Murty and Kanthed [30] presented the thermal performance of a box-type solar cooker with PCM filled in the glass cover to use as transparent insulation during low solar radiation or off sunshine hours, it would not allow the loss of heat from of the solar cooker. Commercial-grade lauric acid (melting point is 42.2 °C and latent heat of fusion is 181 kJ/kg) was used as a latent heat storage material. The PCM solar cooker and reference solar cooker were having 37 cm × 37 cm as aperture area. A

cooking pot made up of aluminum with internal diameter 16 cm, depth 4 cm and thickness 0.5 cm were used for the experiments. The top aperture of the solar cooker was covered with a double walled toughened glass of thickness 0.3 mm with a separation distance of 10 mm. The space between the glass covers of a solar cooker was filled with the PCM. This cooker is referred as 'PCM solar cooker'. A similar solar cooker was taken as a reference cooker. The thermal performance of solar cookers were evaluated by performing the stagnation temperature test called as First figure of Merit (F_1) of the solar cooker. Various parameters like plate temperature, load temperature, temperature of the PCM, intensity of solar radiation and the ambient temperature were measured for the PCM solar cooker. The thermal performance of PCM solar cooker was compared with the reference solar cooker. Authors observed a good transmittance and insulating property during the charging and the discharging processes of the PCM. During charging process, as the PCM melts, it allowed the solar radiation into the solar cooker and improves the cooking performance and during discharging process, as it solidifies, the thickness of the insulating medium increased with time and the rate of heat loss from the system also decreased and hence the heat energy retains for a longer time inside the PCM solar cooker and hence it could be used as a hot case.

In other hand, parabolic solar cooker (PSC) has a unique property of producing higher temperature up to 250 °C. It has a wide range of applications such as making chapattis, baking of food material and distillation, but it creates an inconvenience to the user due to its high amount of glare. Murty et al. [31] designed and developed an inclined heat exchanger unit for SK-14 PSC for off-place cooking. The principal objective of this study was to use an inclined HTF column as heat exchanger unit and to evaluate the thermal performance of a PSC assisted with inclined cylindrical heat exchanger unit for off-place cooking with and without PCM. Experiments were conducted for cooking food on a normal day. Murty et al. [32,33] have also optimized the angle of inclination of the HTF column experimentally. During the experiment (a) effect of variation of the angle of the inclined HTF column on the cooking time was studied and the angle of inclination was optimized. (b) Attempt was made to store the thermal energy in a PCM in a concentric circular cylinder surrounding the cooking vessel obtained from the cylindrical heat exchanger assisted SK14 PSC for further off-time cooking (Figure 6). Commercial-grade sodium acetate (melting point is 104 °C and latent heat of fusion is 230 kJ/kg) and acetanilide (melting point is 115.42 °C and latent heat of fusion is 189.4 kJ/kg) were used as a latent heat storage material. The cooking experiment was conducted with PCM as a thermal energy storage medium, during charging and discharging of the PCM. It was observed that cooking time was less during discharging of the PCM. Thermal energy obtained from a PSC can be transported to a comfortable place for the efficient utilization of solar energy by using an inclined heat exchanger unit. The method can be used for various domestic and industrial purposes. The cooking experiments were also conducted by varying the angle of inclination of the cylindrical heat exchanger unit from 30° to 50° in steps of 5°. The variation of cooking with the angle of inclination of the cylindrical heat exchanger unit is shown in Figure 7. It was observed that cooking time was least for the inclination angle of 45°.

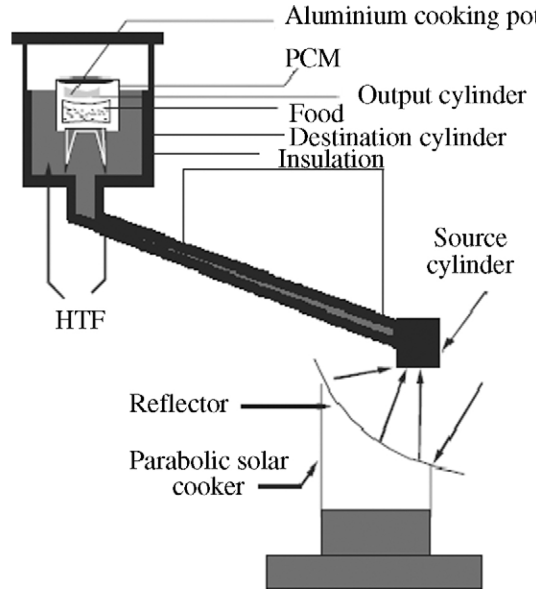

Fig. 6. Schematic of the inclined heat exchanger unit assisted SK-14 PSC.

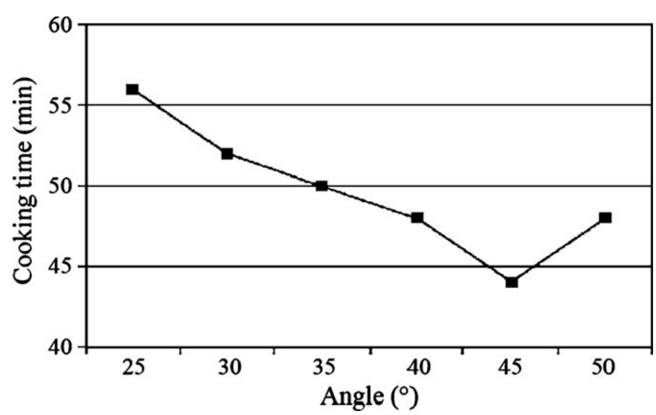

Fig. 7. Variation of cooking time with angle in an inclined heat exchanger unit assisted SK-14 PSC.

Table 2
Thermophysical properties of PCMs used in a box-type solar cooker Chen et al. [34].

Properties	$Mg(NO_3)\cdot 6H_2O$ [18]	Stearic acid [19]	Acetamide [20]	Acetanilide [21]	Erythritol [26–28]
Melting temperature (°C)	89	55.1	82	118.9	118.0
Latent heat of fusion (kJ/kg)	162.8	160	263	222	339.8
Density (kg/m^3)					
Solid	1636	965	1159	1210	1480
Liquid	1550	848	998	1020	1300
Specific heat (kJ/kg °C)					
Solid	1.84	1.6	1.94	2.0	1.38
Liquid	2.51	2.2	1.94	2.0	2.76
Thermal conductivity					
Liquid (W/m °C)	0.490	0.172	0.5	0.5	0.326

Recently, Chen et al. [34] investigated theoretically on the PCMs used as the heat storage media for box-type solar cookers. The selected PCMs are magnesium nitrate hexahydrate, stearic acid, acetamide, acetanilide and erythritol (Table 2). For a two-dimensional simulation model based on the enthalpy approach, calculations have been made for the melt fraction with conduction only. Different material such as glass, stainless steel, tin, aluminium mixed, aluminium and copper are used as the heat exchanger container materials in the numerical calculations. It is also found that the initial temperature of PCM does not have very important effects on the melting time, while the boundary wall temperature play an important role during the melting and has a strong effect on the melt fraction. The results also show that the effect of thickness of container material on the melt fraction is insignificant. The results obtained in this paper show that acetamide and stearic acid, should be used as storage media in a box-type solar cooker to cook and/or to keep food warm in the late evening with different heat exchanger container materials. The large value of thermal conductivity of heat exchanger container material did not make a significant contribution on the melt fraction except for at very low thermal conductivities.

3. Conclusion

Cooking energy plays an important role in sustainable energy management in Indian households as well as worldwide. There are various options to meet the end user needs using both commercial and non-commercial energies. Traditional fuel-wood utilization must be minimized with the developed solar cookers. This will lead to reduction in human drudgery. Such an effort will not only be useful in improving the quality of life but also in environmental protection. This review paper is focused on the available thermal energy storage technology for solar cookers. With the storage unit, food can be cooked at late evening, while late evening cooking was not possible with a normal solar cooker. So that, solar cooker with storage unit is very beneficial for the humans and as well as for the energy conservation. This paper presents the past and current research in this particular field of energy storage for solar cookers.

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